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EVALUATION OF QUANTITATIVE THEORIES OF TIMING

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Scalar timing theory is a clear, complete, modular, and precise theory of timing that explains much of the data from many timing procedures, but not all of the data from all of the procedures. The multiple-time-scale theory of timing provides an alternative representation of time that has not yet been tested with respect to its fit to timing data.

Key words: time perception, timing, scalar timing theory, scalar expectancy theory, pacemaker

The article by Staddon and Higa provides a criticism of scalar expectancy theory (SET) and presents an alternative multiple-time-scale (MTS) theory of timing.

Criticisms of Scalar Expectancy Theory

The authors report that ''in terms of citations and numbers of published papers, SET is by far the most popular theory of interval timing'' (p. 215). This may partly be an historical accident of having been developed earlier than others. Once a theory has been announced and found to be useful, alternative theories are held to the higher standard of being demonstrably better. Four particularly attractive features of SET are that it is clear, complete, precise, and modular (i.e., it consists of separable parts). Realistic alternative theories of time will undoubtedly also have these features.

A distinction should be made between the underlying formal model of scalar timing theory developed in the 1970s by Gibbon (1971, 1972, 1977) and the information-processing interpretation of this process developed in the 1980s (Church & Gibbon, 1982; Gibbon & Church, 1981, 1984; Gibbon, Church, & Meck, 1984). The criticisms of Staddon and Higa apply to the information-processing interpretation of scalar timing theory, particularly its representation of time.

In the information-processing interpretation of scalar timing theory, the assumption was made that psychological time is a single function that changes in some regular way with physical time. This function was assumed to be produced by a pacemaker that emitted pulses at some rate and distribution form that were summed in an accumulator (Gibbon et al., 1984). Although a random emitter and a fixed emitter without variablility would not, as the sole source of variance, produce the Weber-law property, and a fixed emitter without variability was far too regular, multiplicative sources of variance in memory storage and decision threshold produced the Weber law property of interval timing (Gibbon, 1992). One of the strengths of SET was that it did not require a particular distribution form of the interpulse interval to fit data functions that had the Weber law property. Staddon and Higa's conclusion that pacemaker-accumulator mechanisms ''are fundamentally at odds with the Weber law property of interval timing'' (p. 215) suggests that no distribution of interpulse intervals has a constant coefficient of variation (a constant ratio of standard deviation to mean number of pulses at different times), but the Rayleigh distribution has this characteristic (Reid & Allen, 1998), as well as a Poisson or fixed emitter with a variable rate, either between or within trials (Gibbon, 1992). To distinguish between different assumptions about interpulse distributions requires data from extensive psychometric studies with very short time intervals (Fetterman & Killeen, 1995).

In their discussion of the pacemaker, Staddon and Higa gave the impression that the development of SET proceeded as follows: (a) A Poisson pacemaker was assumed, (b) it was found to be incompatible with Weber's law, and (c) the deficiency was corrected by

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adding additional assumptions about memory and decision processes. This is historically incorrect. The development was that (a) an extensive review of the behavioral data supported Weber's law for timing (Gibbon, 1977), and subsequently, (b) an information-processing analysis of scalar timing theory with a Poisson pacemaker, and other distributions, was found to account quantitatively for the data (Church & Gibbon, 1982; Gibbon, 1991; Gibbon & Church, 1984; Gibbon et al., 1984).

Staddon and Higa conclude that the psychological representation of time is approximately a logarithmic, rather than a linear, function of time. This provides part of an explanation of the form of the psychophysical bisection function which is quite symmetrical when the duration of the stimulus is plotted in logarithmic units (e.g., Church & Deluty, 1977). Church and Deluty described a model containing three parts (clock, criterion, and response rule) and considered three functional relationships between physical and psychological time (linear, logarithmic, and reciprocal). They concluded that the simplest explanation of these data was the logarithmic representation of time, although they explicitly recognized that an alternative response rule could be consistent with a linear representation of time. One problem, however, was to resolve why the function relating mean response rate to time in the peak procedure is a fairly symmetrical function. In their first collaborative experiment, Gibbon and Church (1981) attempted to find a single function that would account for both the approximate symmetry of the psychophysical function on a logarithmic axis and the approximate symmetry of the peak function on a linear axis. Staddon and Higa assume that animals use the logarithmic function in the bisection procedure but the inverse function (antilog) in the peak procedure. This dual code may produce some conflicts in a bisection procedure in which the two manipulanda are always available (Platt & Davis, 1983). Can an animal use a linear representation of time to stop responding on one lever and start responding on the other, and a logarithmic representation of the time to decide when to switch between the levers?

In their discussion of the psychological representation of time, Staddon and Higa gave the impression that the development of SET proceeded as follows: (a) A linear representation of time was assumed, (b) it was found to be incompatible with the psychophysical function relating the probability of a long response to stimulus duration, and (c) the deficiency was corrected by adding additional assumptions about memory and decision processes. This is historically incorrect. The development was that (a) in the initial development of an information-processing interpretation of scalar timing theory, there was no satisfactory basis to determine whether the psychological representation of time was linearly or logarithmically related to physical time, (b) the time-left procedure was designed to force the animal to do an operation with its psychological time scale before using it in behavior, (c) clear quantitative results of several time-left experiments were consistent with a linear representation of time, but not with a logarithmic representation of time (Gibbon & Church, 1981).

In their discussion of the analysis of individual trials of the peak procedure, Staddon and Higa gave another example that suggested that the development of SET proceeded as follows: (a) An assumption was made, (b) it was invalidated by data, so (c) a new feature was added to the theory to correct the flaw. They report that, in the peak procedure, (a) an initial prediction of SET was that the later an animal began responding the earlier it would stop, (b) the data showed that the later an animal began responding the later it would stop, therefore (c) SET was modified to correct the flaw. In fact, the purpose of the individual-trials analysis was to decompose the sources of variance from clock, memory, and decision processes based on a quantitative analysis of individual trials (Church, Meck, & Gibbon, 1994; Gibbon & Church, 1992). Previous analyses using mean response functions had emphasized the importance of memory variance, which would lead to the observed positive correlations between the times that an animal starts and stops responding in the peak and temporal generalization procedures (Church & Gibbon, 1982; Gibbon & Church, 1984; Gibbon et al., 1984).

Because scalar timing theory is clear, modular, and precise, it is possible to test the predictions of the theory with different experimental procedures and different dependent measures. In some cases, the predictions have been outstandingly close to the data; in some cases they are obviously wrong; in some cases there are small but systematic differences between the predictions and the data. The failures to fit, even more than the successes, provide the impetus for theoretical development.

One example of a failure is that scalar timing theory (as described by Gibbon et al., 1984) makes no provision for extinction and various related phenomena. Another problem is that it does not account for the behavior in variable-interval schedules of reinforcement without changes that pertain only to some procedures (Brunner, Fairhurst, Stolovitzky, & Gibbon, 1997). A theory of the animal should apply to all procedures, or a procedure-classifier module should be added to the theory. These problems may not be present in vector memory representations used in some well-specified timing theories (Grossberg & Schmajuk, 1989; Machado, 1997), rather than the distribution memory representation used in scalar timing theory.

Examples of small but systematic differences between the predictions of scalar timing theory and the data have been reported in animal experiments (Church, Lacourse, & Crystal, 1998; Crystal, 1999; Crystal, Church, & Broadbent, 1997) and in human experiments (Collyer, Broadbent, & Church, 1992, 1994; Collyer & Church, 1998). These systematic effects may reveal a mechanism that produces a psychological representation of time that is approximately linear but that has local maxima and minima. A multiple-oscillator model of timing (Church & Broadbent, 1990) has provided some qualitative fits.

A Multiple-Time-Scale Theory of Timing

The phrase "theory of timing" is sometimes reserved for quantitative theories that are fully specified such that two independent investigators can apply the theory to fit the results produced by any procedure in the domain of the theory and obtain the same predictions. In order to predict behavior, a timing theory must include (a) a representation of the physical time since the occurrence of an event, (b) a memory of the time of reinforcement, and (c) a response rule.

The phrase "theory of timing" has also been used to refer to a set of ideas or theory fragments that may be worthy of consideration. The primary idea of MTS is that time is represented as the output of a series of cascaded habituation units. The necessary and sufficient conditions for a function to be "pacemaker free" were not described, but the term may refer to a function that is continuous or nonlinear, or one that has multiple inflection points. Real-time conditioning models (such as that of Sutton & Barto, 1981) made use of stimulus traces as the representation of physical time. More recent versions of real-time conditioning models have used a cascade of stimulus traces (Moore & Choi, 1998). Cascades of functions have also been used in the spectral theory of timing (Grossberg & Schmajuk, 1989) and in a version of the behavioral theory of timing (Machado, 1997); parallel coding of multiple periodic functions was used in the multiple-oscillator theory of timing (Church & Broadbent, 1990). In these cases, physical time is coded as a vector of values of multiple functions that change in some regular way with physical time.

Without an explicit proposal about memory storage, memory retrieval, and decision processes, it is not clear the sense in which the MTS theory of interval timing can account for data from many different time-related experiments. Although the article contains 21 equations, there is no quantitative comparison of observed with predicted behavior. None of the 13 figures provides visual evidence of a correspondence between observed and predicted behavior. One approach would be to substitute the output of a series of cascaded habituation units for a pacemaker-accumulator system in scalar timing theory; that is, to change the perceptual representation of time without changing assumptions about memory storage or retrieval or the decision rule. This would provide a basis for a quantitative comparison of the two models (Church, 1997).

Staddon and Higa's critique of SET suggests that it may be possible to develop a timing theory that is simpler, is applicable to a wider range of procedures, is connected more firmly to the biological basis of behavior, and makes more accurate predictions. In my judgment, such a theory will, like SET, be clear, complete, modular, and precise.

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